Noname manuscript No.
(will be inserted by the editor)

Observation of pentaquark states and perspectives of further studies

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Received: date / Accepted: date

The quark model based on quark-antiquark mesons and three-quark baryons has been very successful in classifying the hadrons. However, quantum chromodynamics (QCD) does not forbid the existence of exotic hadronic states with other quark-gluon configurations, such as glueballs (with no quark), hybrids (with quarks and excited gluon), multi-quark states (with more than three quarks), and hadron molecules (bound state of two or more hadrons). It is a long history of searching for all these kinds of states, however, no solid conclusion was reached until the recent discovery of tetraquark and pentaquark states.

The first strong experimental evidence for a pentaquark state, referred to as the $\Theta(1540)^+$, was reported in the reaction $\gamma n \to n K^+ K^-$ in the LEPS experiment [1]. It was a candidate pentaquark state of $uudd\bar{s}$. However, it disappeared in a larger statistics data sample in the same experiment and was most probably not a genuine state [2]. The overwhelming studies in theory and in experiments during that period of time was well accounted in the statement that "The story of pentaquark shows how poorly we understand QCD" [3].

A charged charmoniumlike state $Z_c(3900)$ was observed by BESIII [4] and Belle [5] experiments in 2013 in $J/\psi\pi^\pm$ system of $e^+e^- \to \pi^+\pi^- J/\psi$ at center-of-mass energies around 4.26 GeV. Besides the $Z_c(3900)$, BESIII and Belle also observed a series of charged Z_c states including $Z_c(4020)$, $Z_c(4200)$, and $Z_c(4430)$. These states seem to indicate that a new class of hadrons has been observed [6]. As there are at least four quarks within these Z_c states, they have been interpreted either as tetraquark states with a pair of charm-anticharm

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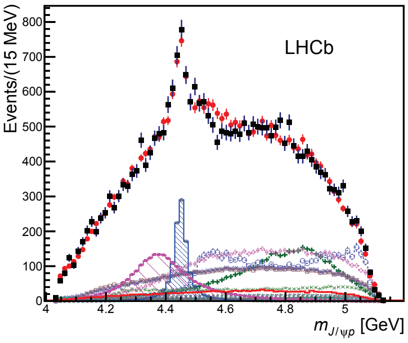

Fig. 1 Distribution of the $J/\psi p$ invariant mass and the fit with two P_c^+ states [7]. The purple hatched histogram is the $P_c(4380)^+$, and the blue hatched histogram is the $P_c(4450)^+$ signal.

quarks and a pair of light quarks, molecular states of two charmed mesons, or other configurations.

Very recently, LHCb experiment reported the observation of two exotic structures, denoted as $P_c(4380)^+$ and $P_c(4450)^+$, in the $J/\psi p$ system in $\Lambda_b^0 \to J/\psi K^- p$ [7]. The $P_c(4380)^+$ has a mass of $(4380 \pm 8 \pm 29)$ MeV/c^2 and a width of $(205 \pm 18 \pm 86)$ MeV, while the $P_c(4450)^+$ is much narrower with a mass of $(4449.8 \pm 1.7 \pm 2.5)$ MeV/c^2 and a width of $(39 \pm 5 \pm 19)$ MeV. Figure 1 shows the fit to the $J/\psi p$ invariant mass distribution and the $P_c(4380)^+$ (purple hatched histogram) and $P_c(4450)^+$ (the blue hatched histogram) contributions. Since the valence structure of $J/\psi p$ is $c\bar{c}uud$, the newly discovered particles consist of at least five quarks.

Several theoretical interpretations of these states have been developed, including a pentaquark doublet, hadronic molecules composed of an anticharm meson and a charm baryon, a $\chi_{c1}p$ resonance for the $P_c(4450)^+$, and so on.

To confirm these pentaquark states, further experimental research should be pursued with the current available and the forthcoming experimental data. There have been many suggestions on the discovery channels for these and other exotic pentaqaurks, such as (1) in B decays: $B^0 \to p\bar{p}K^0$, $\bar{B}^0 \to D^0 p\bar{p}$; (2) in baryon decays: $\Lambda_c^+ \to pK^0\bar{K}^0$, $\Lambda_b^0 \to K^-\chi_{c1}p$; (3) in quarkonium decays: $\Upsilon(nS) \to J/\psi p + X$, $\chi_{cJ}p + X$, and $D^{(*)-}p + X$ $(n = 1, 2, 3)$; (4) in e^+e^- continuum process: $e^+e^- \to J/\psi p + X$, $\chi_{cJ}p + X$, $D^{(*)-}p + X$ and $D^{(*)}\Lambda + X$. It is clear that a systematic search for baryon-meson resonances should be pursed in various processes, where the baryon could be p, Λ, Σ, Ξ, Ω, Σ_c, ..., and the meson be π, η, ω, ϕ, K, D, J/ψ, χ_{cJ}, and so on [8] [9].

The Belle-II experiment is going to take data in 2018, the maximum energy that the Super-KEKB can reach is 11.24 GeV, which is just above the Λ_b-pair mass threshold. The $P_c(4380)^+$ and $P_c(4450)^+$ can be cross checked in the same Λ_b decays if the production cross section of Λ_b is large enough.

It is worth pointing out that the tetraquark and pentaquark candidates mentioned above have a pair of charm-anticharm quarks which may annihilate. Observations of states like T_{cc}^{+} $(cc\overline{ud})$ or Θ_c^0 $(uudd\bar{c})$ or P_{cc}^0 $(ccdd\bar{u})$ or similar serve as better evidences for multiquark states.

In summary, with the observation of the candidate tetraquark and pentaquark states, a new hadron spectroscopy is being revealed. Further studies along this line may strengthen our understanding of how strong interaction works at low energy and thus a better understanding of the matters around us.

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